Toward Routine Autonomous Measurement and Interpretation of Optical Variability in Coastal Waters

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LONG-TERM GOALS

Optical measurements can be used for describing oceanographic processes and for developing predictive models. However, a great deal of time and expertise is required for quality control, data management, and interpretation of results. The full potential of optical observation technology for oceanography will be realized only when appropriate measurements can be made routinely, with automatic generation of robust interpretations. Toward that end, our long-term goal is to broaden the utility of radiometric measurements (upwelling radiance and downwelling irradiance) in coastal waters so that turnkey systems can be developed for the generation of derived data, suitable for use by non-experts.

OBJECTIVES

This program of research is aimed at developing and testing ways to interpret water-leaving radiance and downwelling irradiance as measured by radiometer buoys and subsurface irradiance sensors (k-chains) in coastal waters. Complementary measurements with profiling optical instruments and airborne radiometers are also addressed. Efforts are directed toward: (1) refining and testing algorithms relating optical measurements to optical, biological and chemical properties of surface waters; and (2) supporting efforts to obtain novel information from autonomous measurements of ocean color (e.g., taxonomic information for phytoplankton, effective penetration of biologically and photochemically active radiation, photochemical and biological reaction rates, influence of bubbles).

APPROACH

This work is closely coordinated with the NSERC/Satlantic Industrial Research Chair in Environmental Observation Technology, a partnership between John Cullen (the Chair), Dalhousie University and Satlantic. The Research Chair facilitates a broad range of collaborative research (see "Related Projects"). This ONR project provides funding for additional technical support from Satlantic which complements Dalhousie-based efforts. The approach is to pursue basic questions in bio-optics

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14. ABSTRACT
Optical measurements can be used for describing oceanographic processes and for developing predictive models. However, a great deal of time and expertise is required for quality control, data management, and interpretation of results. The full potential of optical observation technology for oceanography will be realized only when appropriate measurements can be made routinely, with automatic generation of robust interpretations. Toward that end, our long-term goal is to broaden the utility of radiometric measurements (upwelling radiance and downwelling irradiance) in coastal waters so that turnkey systems can be developed for the generation of derived data, suitable for use by non-experts.

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during collaborative research projects and to use this ONR-sponsored effort to improve technologies for measurement, data analysis and interpretation. Integrated with this are the university-based research programs of Lewis and Cullen, directed toward improved interpretations of near-surface optical measurements.

WORK COMPLETED

Measurements of optical properties in surface waters. Optical measurements were made during a NOAA-supported cruise in the southeastern Bering Sea during the late spring of 2001. A hyperspectral radiometer buoy, which measures downwelling irradiance and upwelling radiance from 397-800nm, with ~3.3nm resolution, was deployed as a surface drifter on station while profiles of downwelling irradiance and upwelling radiance were measured in 13 wavebands in the UV and visible range, along with temperature, conductivity and fluorescence, using an irradiance profiler. During the cruise we performed 92 CTD casts, 39 deployments of the hyperspectral radiometer and/or profiler, and 27 drops of a bio-optical package (ac-9 absorption-attenuation meter and a Hydroscat-6 spectral backscatter sensor). We encountered massive phytoplankton blooms clearly observable in images from space (http://visibleearth.nasa.gov/Regions/Bering_Sea/). Our optical measurements with concurrent determination of dominant species led to the development of an approach for obtaining information on taxonomic composition of blooms from remote sensing (Fig. 1); quantitative information on the optics of a coccolithophore bloom (Davis et al. 2000) will be incorporated into future analyses.

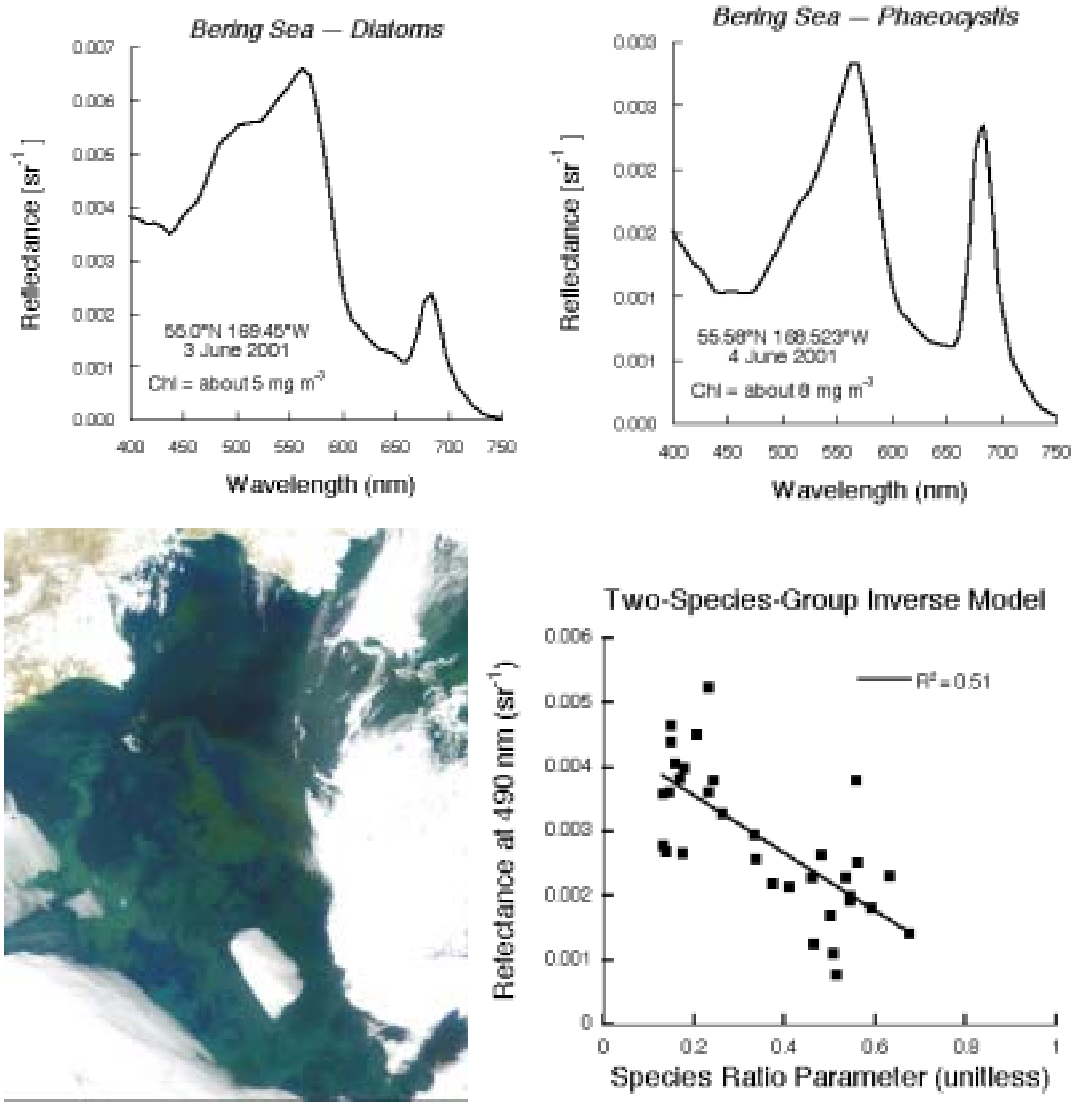
Optical moorings in coastal waters. We supported the deployment for four months of two optical moorings at an aquaculture site in Ship Harbour Nova Scotia. The project is led by A. Cembella and D. Ibarra (Cembella et al. 2001; Ibarra et al. 2001). Continuous measurements include multispectral upwelling radiance, and attenuation coefficients, $K_d(490)$, in four subsurface strata. Supporting measurements include multispectral irradiance profiles, deployments of our bio-optical package and extensive analysis of water samples. Data will be analyzed by D. Ibarra to assess the impact of aquaculture on phytoplankton, and will also be a rich resource for our research on bio-optical variability in coastal waters.

Ultraviolet radiation. Working with H. Browman and R. Vetter, we developed new analyses to describe the effects of UV radiation on DNA damage in eggs and larvae of copepods and cod. Multivariate analysis of experimental irradiance spectra and introduction of a nonlinear model allowed us to describe in unprecedented detail the exposure-response and spectral dependence of DNA damage. The approach can be used to describe biological or chemical effects of UV in surface waters.

Communication of results. Several ongoing lines of research were advanced during preparation of manuscripts and presentations. Spectral parameterizations of water column transparency were described in the context of photosynthesis models (Lehmann et al. 2000, 2001); a comprehensive extension of the work was validated through comparison with a fully spectral model of photosynthesis under a huge range of environmental and physiological conditions (Cullen et al. 2000, 2001); a new method for quantifying the influence of dominant phytoplankton cell size on the optical properties of surface waters was reported (Ciotti et al. 2000, 2001); the interpretation of a widely used diagnostic of physiological status (variable fluorescence, Fv/Fm) was fundamentally revised (Parkhill et al. 2001); estimates of UV attenuation and CDOM absorbance spectra from visible reflectance were presented (Johannessen et al. 2001); and key aspects of physical forcing on ecosystem dynamics were reviewed, from two different modeling perspectives (Cullen et al. 2002; Bissett et al. 2001) — each approach links physical forcing to optically discernible biological responses (e.g., as related to dominant cell size; Ciotti et al. 1999, 2001). In addition, we have significantly advanced our understanding of theoretical aspects of backscattering in the ocean (Zhang et al., 2001), and explored the implications of optical variability on mesoscale and basinscale variability in both biological and physical processes (Lewis, 2001, McClain et al., 2001, Murtugudde et al. 2001, Turk et al. 2001a,b,c).

RESULTS

Influences of phytoplankton communities and physiological status on ocean color. Sampling of widespread phytoplankton blooms in the Bering Sea (Fig. 1) provided an outstanding opportunity to explore novel quantitative interpretations of ocean color (upwelling radiance normalized to downwelling irradiance). Measurements with a hyperspectral radiometer buoy revealed pronounced differences between waters thick with diatoms and a bloom of the colonial prymnesiophyte *Phaeocystis*. Although each bloom was greenish (maximum reflectance was near 550 nm for each), other features of the spectra differed: the *Phaeocystis* bloom was much darker (see the scale ranges for reflectance), the shapes of the spectra between 400 and 550 nm (strongly influenced by the absorption of light by phytoplankton pigments) differed significantly, and the magnitude of the reflectance peak near 685 nm (chlorophyll fluorescence) was much greater for the *Phaeocystis* assemblage.



1. Reflectance as measured with a Satlantic Hyperspectral Radiometer Buoy in the Bering Sea during June 2001. During deployment, the radiance sensors are 0.65m below the surface, so the measurement is $Lu(\lambda, 0.65m)/Ed(\lambda,0^+)$ (sr^{-1}), plotted here as a function of wavelength, λ. Note the different scales for diatoms (upper left) vs. **Phaeocystis** ***(upper right); the diatom bloom is brighter (reflectance is more than two-fold greater). These two water types probably correspond to the swirls of light green and dark green water in a SeaWiFS image taken the same week (lower left: an image of blooms in the Bering Sea provided by the SeaWiFS Project, NASA's Goddard Space Flight Center, and ORBIMAGE). A new inverse model of ocean color as influenced by diatoms vs*** **Phaeocystis** ***(Huot, Ciotti, and Cullen) yields a species ratio parameter for each of 33 reflectance spectra from the cruise (0 = all diatoms, 1.0 = all*** **Phaeocystis*****). Preliminary results (a plot of reflectance at 490 nm vs the species ratio parameter; lower right) indicate that the brighter waters (higher reflectance at 490 nm) are dominated by diatoms. This method for discriminating species composition will be evaluated by direct comparison to pigment analysis and results of microscopic examination. Information content of the fluorescence signal will be examined in targeted studies on the interpretation of sun-induced fluorescence.***

Extending our quantitative description of how dominant size-classes of phytoplankton influence the absorption of light in the ocean (Ciotti 1999; Ciotti et al. 1999, 2001), we developed an inverse model to retrieve the relative influences of diatoms versus *Phaeocystis* on reflectance spectra, ignoring the fluorescence signal. Based on an earlier inverse model which resolved the influence of only one type of phytoplankton in the presence of CDOM and suspended particulate matter (Roesler and Perry 1995), this new approach uses the shapes of independently measured absorption spectra for diatom assemblages and *Phaeocystis* as basis vectors and estimates statistically the relative contribution of each to any observed reflectance spectrum. The resulting parameter, a *Phaeocystis*/diatom ratio (Fig. 1) represents the new kind of data product that we want to develop and evaluate rigorously. At this early stage, we can say that it resolves consistent differences between samples that correlate with optical differences between species groups and help to explain features in ocean color, such as the differing brightness of bloom filaments. Quantitative analysis will follow, especially comparisons between the species parameter and independent determinations of species and pigment composition.

Parameterization of spectral transparency and biological effects. We made further progress in the development of simplified models of photosynthesis based on weighted transparencies of the form:

$$T_{\mathrm{PUR}}^{\mathrm{w}} = \sum_{\lambda=400\mathrm{nm}}^{700\mathrm{nm}} \frac{1}{K_{\mathrm{d}}(\lambda)} \cdot \frac{a_{\mathrm{p}}(\lambda) \cdot E(\lambda, 0)}{\overline{a_{\mathrm{p}}(\lambda)} \cdot E_{\mathrm{PAR}}(0)} \cdot \Delta\lambda \qquad .$$

In this weighting for photosynthetically utilizable radiation (E_{PUR}), the spectrum of surface solar irradiance (normalized to the integral, E_{PAR}) is weighted by normalized photosynthetic absorption and the spectral transparency of the water ($1/K_{\mathrm{d}}(\lambda)$). Full spectral numerical calculations of water column photosynthesis under a reference solar irradiance spectrum could be almost exactly matched by very simple parameterizations of transparency weighted for E_{PUR} and inhibiting radiation, E_{PIR} (Lehmann et al., 2000, 2001). For the next step (Cullen et al., 2000, 2001), we constructed non-dimensional parameters (e.g., $E^{*}_{\mathrm{PUR}} = E_{\mathrm{PUR}}$ normalized to the saturation irradiance for photosynthesis, E_{k}) that could be related statistically to the results of a very large array of numerical simulations of water column photosynthesis, $P_z(t)$ and the inhibition of photosynthesis by UV. The equations:

$$P_Z(t) \cdot \frac{K_{\mathrm{d}}(490)}{P_{\mathrm{s}}^{\mathrm{B}} \cdot B} = \beta_1 (E_{\mathrm{PUR}}^{*}(t))^{\beta_2} \cdot (E_{\mathrm{PUR}}^{*}(t))^{\beta_3 \cdot \ln(E_{\mathrm{PUR}}^{*}(t))} \cdot (T_{\mathrm{PUR}}^{*}(t))^{\beta_4} \cdot (T_{\mathrm{PIR}}^{*}(t))^{\beta_5}$$

$$(\%\mathrm{inhibition})_Z(t) = \varphi_1 (E_{\mathrm{PUR}}^{*}(t))^{\varphi_2} \cdot (E_{\mathrm{PUR}}^{*}(t))^{\varphi_3 \cdot \ln(E_{\mathrm{PUR}}^{*}(t))} \cdot (T_{\mathrm{PUR}}^{*}(t))^{\varphi_4} \cdot (T_{\mathrm{PIR}}^{*}(t))^{\varphi_5}$$

described nearly all the variability in calculated results for a comprehensive range of solar elevation, water types, physiological parameters and ozone concentrations. To the best of our knowledge, this is the first full-spectral parameterization of UV effects on water column photosynthesis. It represents an extremely efficient method for reproducing cumbersome spectrally-resolved calculations of irradiance-dependent processes in the water column. The dimensionless parameters can be derived from measurements of ocean color and published functions describing photosynthesis and DNA damage.

IMPACT/APPLICATIONS

The research associated with this project, along with rapid advances by other workers, is moving us steadily toward achieving the stated goal of developing turnkey systems for measuring upwelling radiance and downwelling irradiance in surface waters and delivering derived data on biological and photochemical processes and the variability of important constituents of surface waters. The simple parameterizations of spectrally-dependent processes and the potential retrieval of information on species composition in algal blooms have strong potential for wide use. Much of this will be tested during sustained deployments of coastal moorings, begun this year and to be enhanced significantly next year, with measurements of hyperspectral reflectance and multispectral attenuation coefficients planned at four mooring sites in coastal waters. The link between ocean optics and UV research (photochemistry and photobiology) has been established and will continue.

TRANSITIONS

Interest in this work, and broader issues associated with the PI's research, is reflected in frequent inquiries from colleagues, requests for lectures on UV effects (Cullen et al. 2000) and ocean fertilization (Cullen 2000, 2001; see also Chisholm et al. 2001), and appointment of J. Cullen to the steering committee of the Coastal Ocean Observation Panel of the Global Ocean Observing System. Cullen was also requested to contribute a chapter on early warning, detection and prediction of blooms for a book on Monitoring and Management Strategies for Harmful Algal Blooms in Coastal Waters, to be published and distributed broadly by APEC (Asia Pacific Economic Program). He and Marcel Babin (Laboratoire d'Océanographie de Villefranche) are also co-convenors of a planned international workshop on real-time coastal observation systems.

Moored radiometer/k-chain systems, of the type developed and examined as a central part of this research effort, are now incorporated in the Gulf of Maine Observation System and are planned for long-term deployment in waters of France, Ireland, and in Nova Scotia.

RELATED PROJECTS

1) NSERC/Satlantic Industrial Research Chair: this partnership is the central source of support for instrumentation, field work, lab studies, and university salaries. Funding for complementary projects, such as this ONR program, are highly leveraged by the research partnership.

2) W.L. Miller, Dalhousie (ONR): photochemical processes and optical properties of surface waters. We participate in the cruises, share data, collaborate on analysis, and participate actively in the supervision of student research. In particular, the quantitative analyses that we develop, such as methods for obtaining spectral weighting functions (e.g., in collaboration with Howard Browman, Inst. Marine Research, Storebø, Norway) and parameterizations of reflectance spectra, are modified for photochemistry applications. This collaboration has generated a number of publications from graduate research, and more are in preparation.

3) NOAA-funded work in the Bering Sea (J. Cullen and R. Davis): optical observations from ships, moorings, and drifters are used to describe bio-optical variability in the Bering Sea as related to physical forcing (P.J. Stabeno, NOAA) in the context of fisheries oceanography (J. Napp, NOAA). Funding from ONR allows us to append extra research on optical properties, including advanced analysis of hyperspectral reflectance spectra..

4) ONR-funded research by Marlon Lewis and colleagues (HyCODE). This project is discussed in a separate report, in which Lewis's activities are described in more detail. We share data and discuss results for these complementary activities.

5) We work with Allan Cembella if the Institute of Marine Biosciences, National Research Council of Canada on optical detection of biological variability near aquaculture sites. The emphasis is on detection and prediction of harmful algal blooms. The first extended deployment of moored systems (conducted by graduate student D. Ibarra) has been a success, and the data stream will be used in further development of our program.

6) Research on harmful algal blooms (with Don Anderson, WHOI), partially funded by NSERC and the ECOHAB program, provides information on physiological and optical characteristics of phytoplankton (including fluorescence) that is directly relevant to bio-optical characterization of coastal waters.

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